

# M1 Mirror Print-Thru Investigation and Performance on the Thermo-Opto-Mechanical Testbed for the Space Interferometry Mission

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## ABSTRACT

SIM PlanetQuest (SIM) is a large (9-meter baseline) space-borne optical interferometer that will determine the position and distance of stars to high accuracy. With microarcsecond measurements SIM will probe nearby stars for Earth-sized planets. To achieve this precision, SIM requires very tight manufacturing tolerances and high stability of optical components. To reduce technical risks, the SIM project developed an integrated thermal, mechanical and optical testbed (TOM3) to allow predictions of the system performance at the required high precision. The TOM3 testbed used full-scale brassboard optical components and picometer-class metrology to reach the SIM target performance levels. During the testbed integration and after one of the testbed mirrors, M1, was bonded into its mount, some surface distortion dimples that exceeded the optical specification were discovered. A detailed finite element model was used to analyze different load cases to try to determine the source of the M1 surface deformations. The same model was also used to compare with actual deformations due to varied thermal conditions on the TOM3 testbed. This paper presents the studies carried out to determine the source of the surface distortions on the M1 mirror as well as comparison and model validation during testing. This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

**Keywords:** mirror, bonding, surface deformation

## 1. INTRODUCTION

The SIM PlanetQuest (SIM) mission [1,2] is part of the strategic NASA program to search for Earth-like planets in the habitable zones of nearby stars. The SIM instrument is an optical interferometer system with a 9 meter baseline, which includes two sets each of one “science” interferometer to perform astrometric measurements on target stars, and two “guide” interferometers used for spacecraft pointing reference.

All six interferometers are similar; each of the science interferometers consists of a collector telescope, composed of a 336 mm diameter flat siderostat (SID) that pivots to change target stars, and a compressor telescope (CMP) that accepts the 304.5 mm beam from the SID and reduces it to 35 mm, sending a collimated beam to a combiner system via a steering mirror and a set of relay optics. In the center of the SID there is a double cube-corner (DCC) that serves as a fiducial for the metrology system in charge of determining the pathlength differences in the interferometer. The DCC is aligned very precisely so that its vertex is within a few microns of the front surface plane of the SID flat, and centered on the diameter of the mirror. The pathlength changes of the siderostat in each interferometer must be known to tens or hundreds of picometers, depending on the type of observation. This precision requirement means that the position of the DCC relative to the SID flat must be very stable, because once SIM is on-orbit and operating, the DCC provides the reference point for the position of each of the siderostats and there is no independent way to verify the position of the DCC relative to the flat surface of the SID.

In order to verify the feasibility of the tight requirements levied upon this instrument, the SIM program has developed a series of technology demonstration milestones. Some of these milestones are proven through a series of testbeds. A thermo-opto-mechanical testbed (TOM3) was developed to show both that this level of stability is achievable and that its performance can be accurately modeled. Of particular importance is the modeling aspect due to the physical size and the required precision of SIM: full scale tests of such a system will be very expensive, if at all possible; and if we are able to

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demonstrate that the analytical models provide the required accuracy, the number or size of tests can be reduced while maintaining high reliability at an acceptable risk level. The TOM3 experiment was one of the key ground-based testbeds that allowed us to demonstrate some critical technologies for SIM [3,4].

The high precision interferometry required by SIM needs extremely accurate knowledge of optical path length changes, and therefore extremely precise internal metrology, which is to be carried out with near-infrared laser heterodyne metrology gauges. In order for SIM to succeed, the optical path length metric provided by the interferometer fringe determination, under the flight thermal environment, must be extremely consistent with the distances measured by metrology gauges at the level of tens of picometers. The purpose of TOM3 was to demonstrate this agreement in a full-scale simulation that implements the front-end fraction of the final SIM flight functionality. In addition, TOM3 enabled us to verify and correlate the results obtained during testing through various environmental conditions, using high fidelity analytical models.

## 2. THE THERMO-OPTO-MECHANICAL TESTBED

The TOM3 testbed consists primarily of two brassboard test articles (SID and CMP), a metrology system based on a common-path heterodyne interferometer (COPHI), a chopping/fold mirror (CM), and a thermal shroud for controlling the environment around the SID. The optical components are mounted rigidly to an optical bench located inside a vacuum chamber as shown in Figure 1. The testbed layout is shown in Figure 2. In order to provide mechanical stability, the optical bench is supported within the chamber by four air isolation legs that are outside the chamber. Soft bellows feedthroughs in the chamber allow the air isolators to remain outside the chamber without affecting the isolation. The thermal shroud is mounted to the chamber wall and does not come in contact with the optical table or any optical components. Cutouts in the lower panel of the shroud allow the bipods supporting the SID to pass through without contacting the shroud.

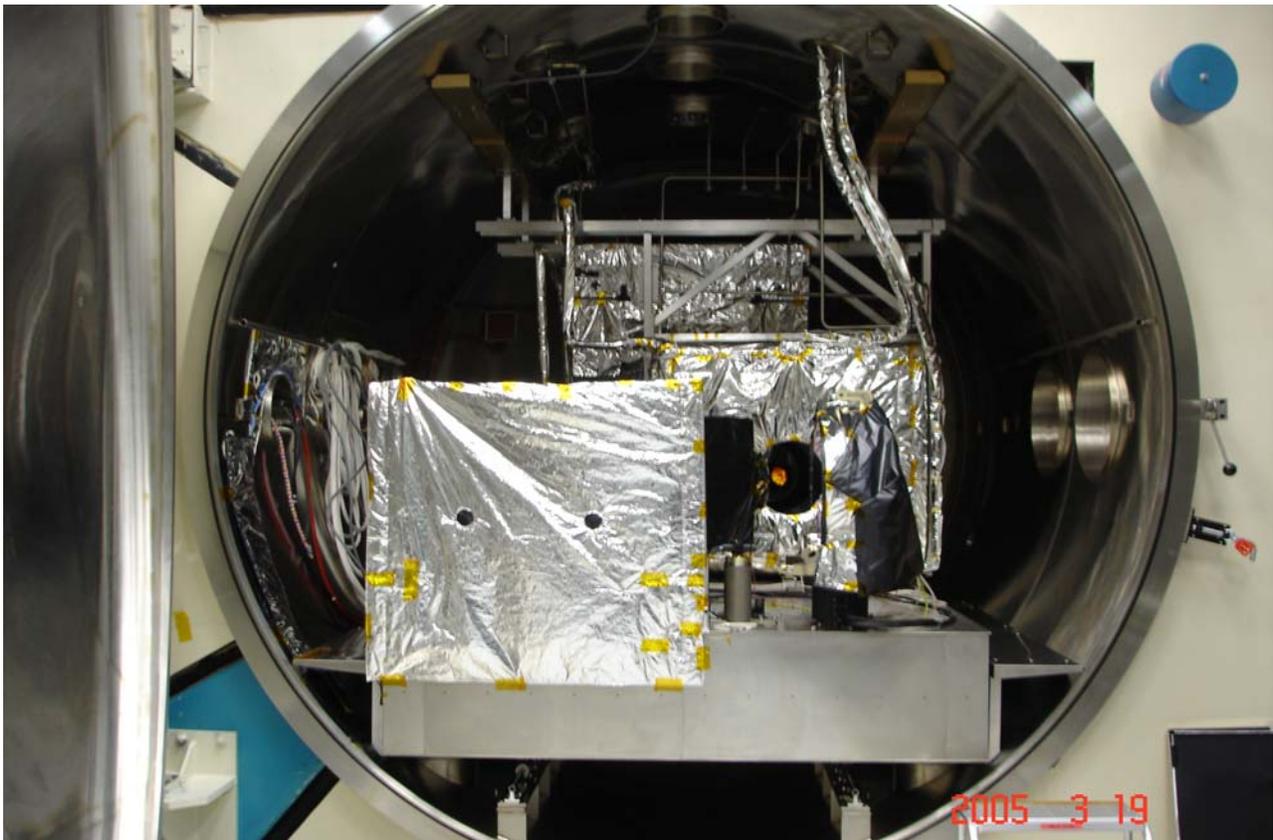


Figure 1 - TOM3 Testbed in 3.3 m Test Chamber.

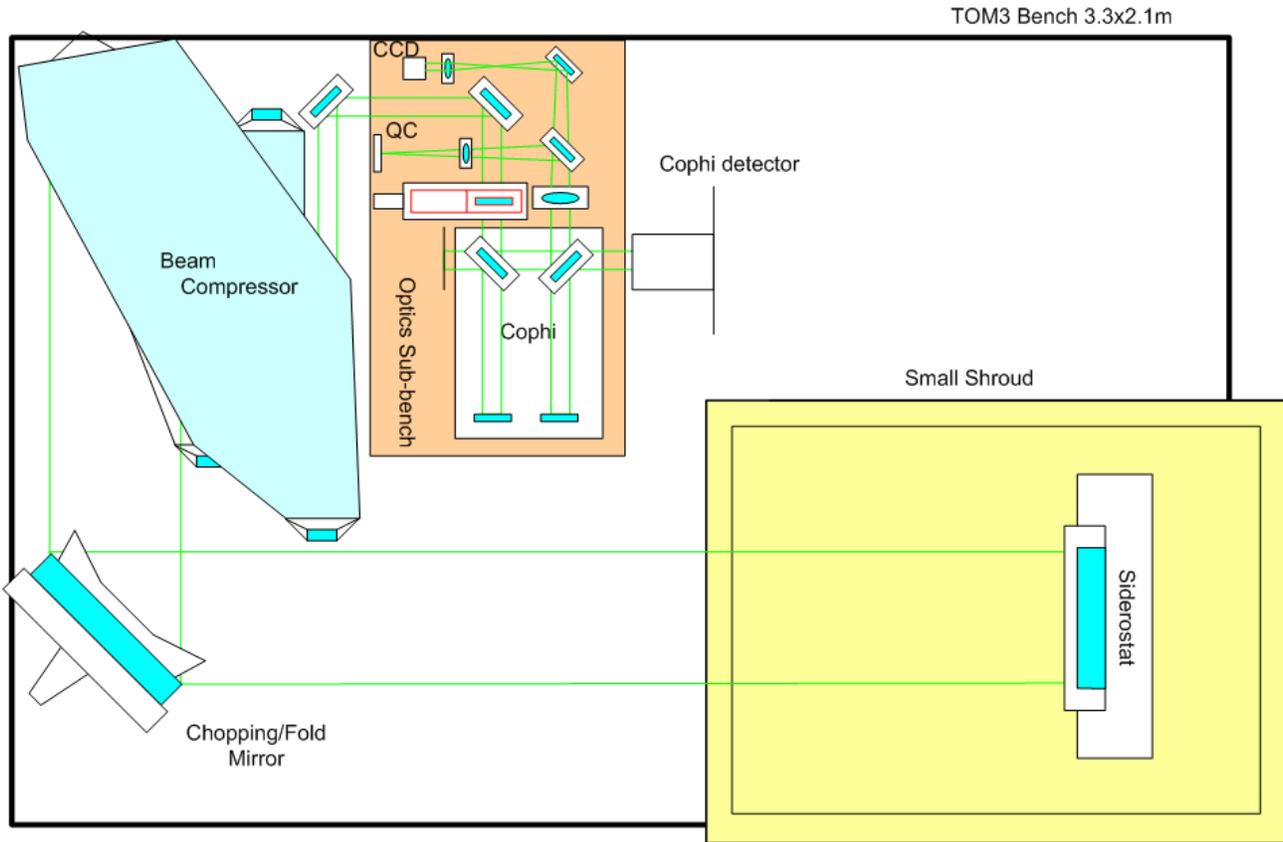


Figure 2 - TOM3 Testbed Layout.

The chopping/fold mirror can be used as shown in Figure 2 to measure the Beam Compressor and Siderostat simultaneously or, alternatively, rotated counterclockwise facing directly into the compressor in retro mode to measure the Beam Compressor only.

### 3. BRASSBOARD BEAM COMPRESSOR

The Compressor Bench Assembly is designed to receive optical starlight reflected from the Siderostat Mirror Assembly. The compressor is a three-mirror anastigmatic telescope design, with a flat fold mirror to make it compact. This light is then “compressed”, and at that point it leaves the Compressor and hits the Fast Steering Mirror (FSM). The optical path is shown in Figure 3; Table 1 lists the major components, their general function, mass and fabrication source. In the TOM3 testbed it is used in reverse to expand the COPHI beam to the diameter of the SID. The Compressor Assembly consists of a large carbon fiber composite bench which contains four static mirror assemblies: the primary mirror (M1), secondary mirror (M2), fold mirror (FM), and the tertiary mirror (M3). The composite panels are fabricated using an egg-crate structure to provide the required stiffness.

The Compressor bench was not located within the thermal shroud and was instead passively thermally controlled with multi-layer insulation (MLI) blankets. The lack of thermal control made the bench susceptible to diurnal temperature changes in the chamber wall as well as soak changes from the presence of the cold liquid nitrogen (LN2) shroud inside the chamber.

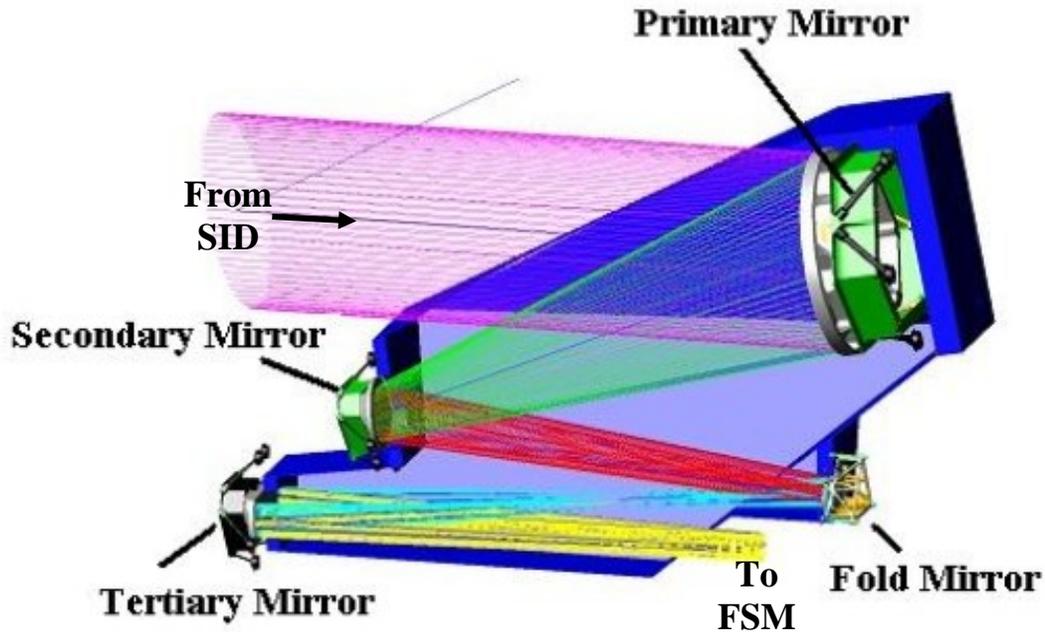


Figure 3 - Compressor Bench Optical Path

Component	Function	Material	Mass (kg)	Vendor
Compressor Bench	Ultra-Low CTE Support For Compressor Optics	M55J	16.5	ATK
M1 Mirror Glass	Receives 35cm Optical Beam From Siderostat	ULE	5.6	Tinsley
M1 Mirror Mount	Supports M1 Mirror	Invar	2.5	JPL
M2 Mirror Glass	Receives Optical Beam From M1	ULE	0.5	Tinsley
M2 Mirror Mount	Supports M2 Mirror	Invar	0.4	JPL
Fold Mirror Glass	Receives Optical Beam From M2, Inverts Signal	ULE	0.2	Tinsley
Fold Mirror Mount	Supports Fold Mirror	Invar	0.3	JPL
M3 Mirror Glass	Receives Optical Beam From Fol Mirror	ULE	0.7	Tinsley
M3 Mirror Mount	Supports M3 Mirror	Invar	0.4	JPL

Table 1 - Brass-Board Compressor Hardware List

#### 4. COMPRESSOR PRIMARY MIRROR

The current paper presents analysis performed on the primary mirror of the compressor. In general, the finite element models (FEMs) of all mirrors inside the Compressor Bench, M1, M2, M3 and FM, were done at JPL. These picometer level models were created using solid, parabolic and linear, wedge and tetrahedron elements. The material properties were assumed to be constant with respect to temperature. The high fidelity FEM for M1, the largest mirror in the compressor is shown in Figure 4. Table 2 gives the material properties used in the modeling of M1. The FEM of the M1 mirror has approximately 98,000 nodes and 49,000 elements.

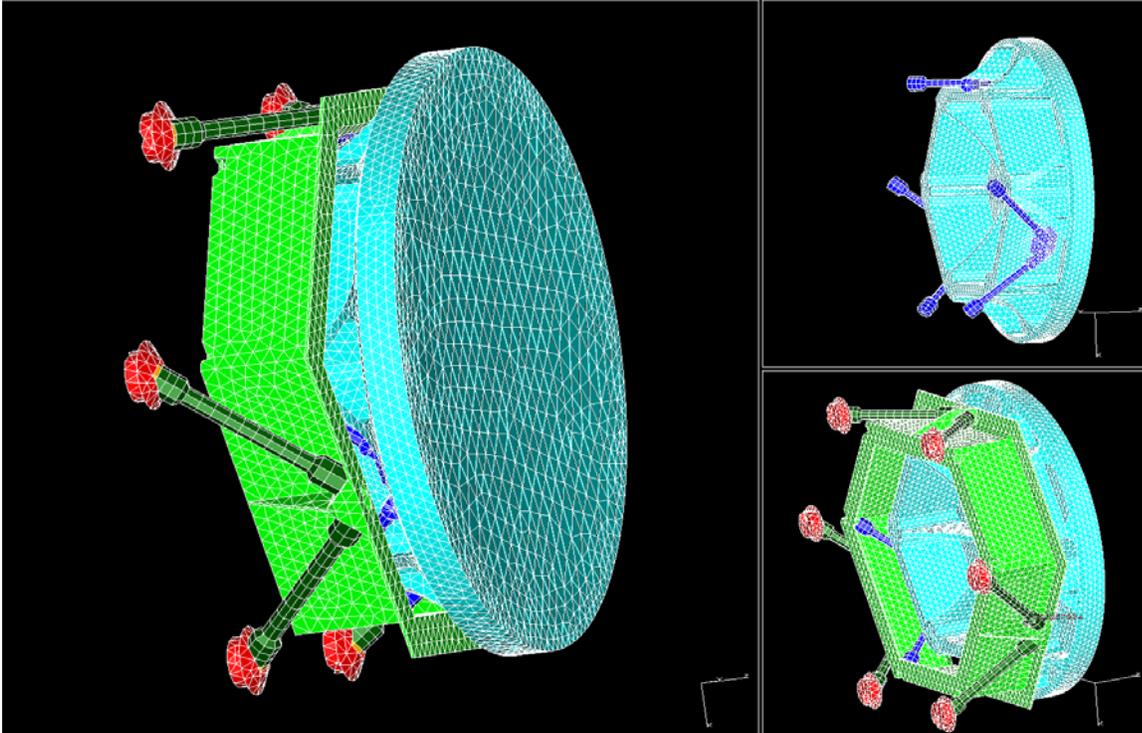


Figure 4 - Model of M1 (Compressor Primary Mirror) and mounts. Similar models were made of all four mirrors in the CMP.

Property	Invar	7972 ULE	3M 2216 Gray Bond
Young's Modulus, E [Pa]	1.4134E+11	6.7569E+10	9.9726E+08
Poisson's Ratio, $\nu$	0.29	0.17	0.46
Modulus of Rigidity, G [Pa]	5.4813E+10	2.8958E+10	3.4129E+08
Coefficient of Thermal Expansion, $\alpha$ [ $\Delta l/l/^\circ K$ ]	1.2600E-06	1.9998E-08	1.0200E-04
Mass Density, $\rho$ [ $kg/m^3$ ]	8112.07	2208.23	1318.39

Table 2 - Material Properties used for M1 mirror

## 5. ANALYSIS OF M1 PRINT-THRU

The compressor with all mirrors mounted to it was delivered to the TOM3 team, but a significant print-thru on the M1 mirror surface was observed at the fabricator after the mirror was bonded to the JPL bipods and mount (Figure 5, left). A similar pattern print-thru was also observed on the fully assembled compressor. Since the mirror FEMs were developed primarily to provide distortion results due to applied thermal loads, the investigation of the print-thru provided an excellent opportunity to further test the predictions of the structural models under different loading conditions.

Analyses of the distortion were carried out using the picometer level FEM of the M1 mirror, including gravity deformations, bonding shrinkage, thermal distortion analysis, etc. In addition, several misalignment schemes were also analyzed.

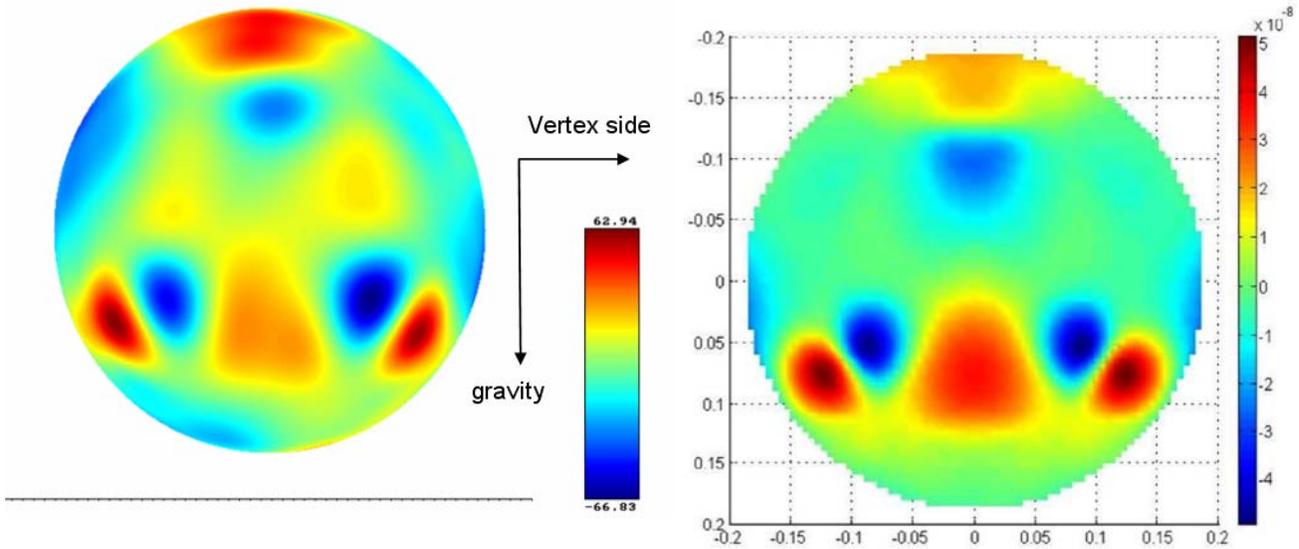


Figure 5 - M1 Mirror Print-Through showing 20 nm rms equivalent surface error, 129.8 nm peak-to-valley (P-V) (left). FEA combined case. M1 Mirror Analysis Results including 1 G gravity on bipods. Rms surface error is 14 nm, P-V is 103 nm. (right)

After the study was completed, it was determined that improper fixture support during surface figure measurements led to polished-in dimples, as depicted in Figure 6. When the mirror was in the test fixture, the mirror deformation affected the surface. A surface map was taken and the information conveyed to the polishing machine. During polishing, the surface was polished with the inherent defect. So, during surface measurement, the mirror would show a perfect surface, but after removing the load caused by the test fixture, the dimples will show up. For a planar or concentric mirror, the manufacturer would rotate the mirror several times in order to be able to subtract the gravity effect. But since this particular mirror is an offset parabola, rotating the mirror was more complicated because the measuring equipment would have had to be repositioned during the surface map measurements and due to schedule constraints this was not done.

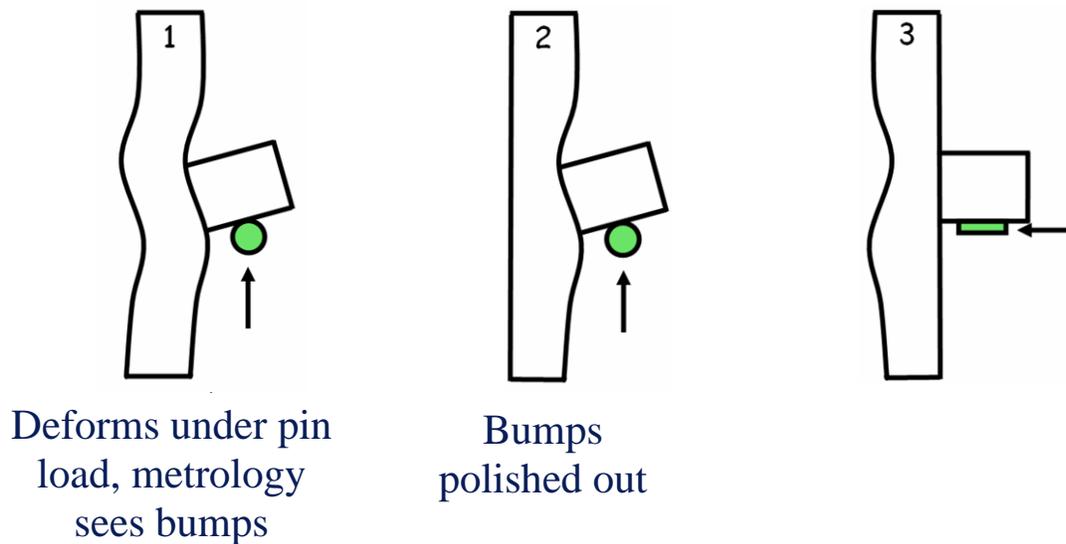


Figure 6 – Deformation of mirror surface under metrology fixture loading.

Figure 7 also show the how the reaction forces interact with the mirror. The design of the mirror mounts calls for bipods which inherently do not take loads in the perpendicular direction, but rather only in the direction of the bipods, as shear loads, as shown in Figure 7. On the other hand, the load applied by the testing fixture applied a normal load to the mirror which in turn caused the deformation of the mirror surface. Additionally, the testing fixture was applying the load on the mirror at its weakest points, that is, at a location where the mirror did not have stiffening ribs.

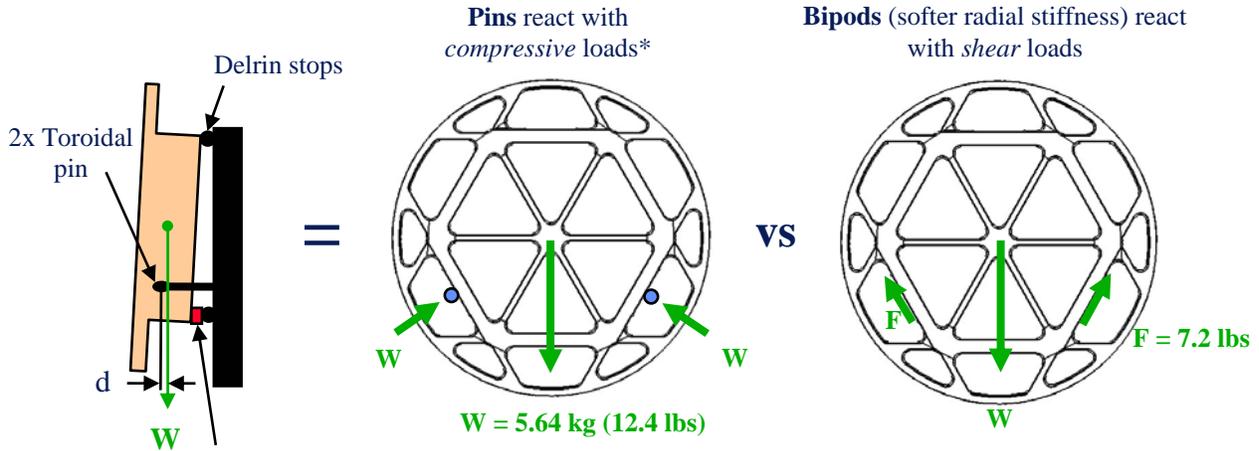


Figure 7 – Force reactions on mirror due to pin and bipod supports

The analysis matched the shapes and amplitude (to the same order) of the measured error. The distortion mechanisms were also reviewed and concurred by the manufacturer. It is estimated that this problem accounted for about 2/3 of total distortion problem. Additionally, it was determined that inadequate mirror mount design also contributed to the overall distortion. Wave front error (WFE) changes during shimming and mounting into the Compressor Bench were also observed. This problem was due to a soft offload ring and stiff supports (bipods, hexapods).

The combined finite element analysis (FEA) results for machined dimples, gravity sag and post-mounting hanging case are shown to the right in Figure 5. These results compared very well, both in magnitude and shape, with the mirror map shown to the left in Figure 5. The RMS values shown are within 30%, and the peak-to-valley (P-V) values are within 20%. It would have been possible to obtain a better correlation of the results by identifying better values for some of the physical parameters, but in the interest of time the results were sufficiently convincing and were deemed appropriate.

In order to verify the claim that the dimples were polished-in, a simple test was developed to try to remove the dimples from the glass surface. The test tried to mimic the force applied to the mirror by the measuring fixture at Tinsley, which produced a radial force equivalent to the mirror weight. For the test, two plungers were mounted on the side of the mirror, pressing the bipod mounts in the radial direction. Surface maps were obtained with and without the plungers and then subtracted. The result is a map of the mirror with the plungers action only, without the effect of gravity, surface defects, etc. Figure 8 (left) shows a map obtained from the TOM3 testbed and Figure 8 (right) shows the analysis results obtained by applying an equivalent force produced by the plungers on the M1 mirror. Visual analysis of the results shows good correlation between the two surface maps.

The RMS results calculated with the analytical model were approximately 10% higher than the measured surface map RMS value. The P-V values are off by about 60% and this could be attributed to the uncertainty in the boundary conditions, as the force applied by the plungers could not be measured directly but was calculated from the manufacturer’s specification and the number of screw turns used to apply the force. At this time further investigation to improve model correlation was not deemed required, since the main purpose of this test was to confirm that the testing fixture used during manufacture was indeed the culprit in creating the dimples.

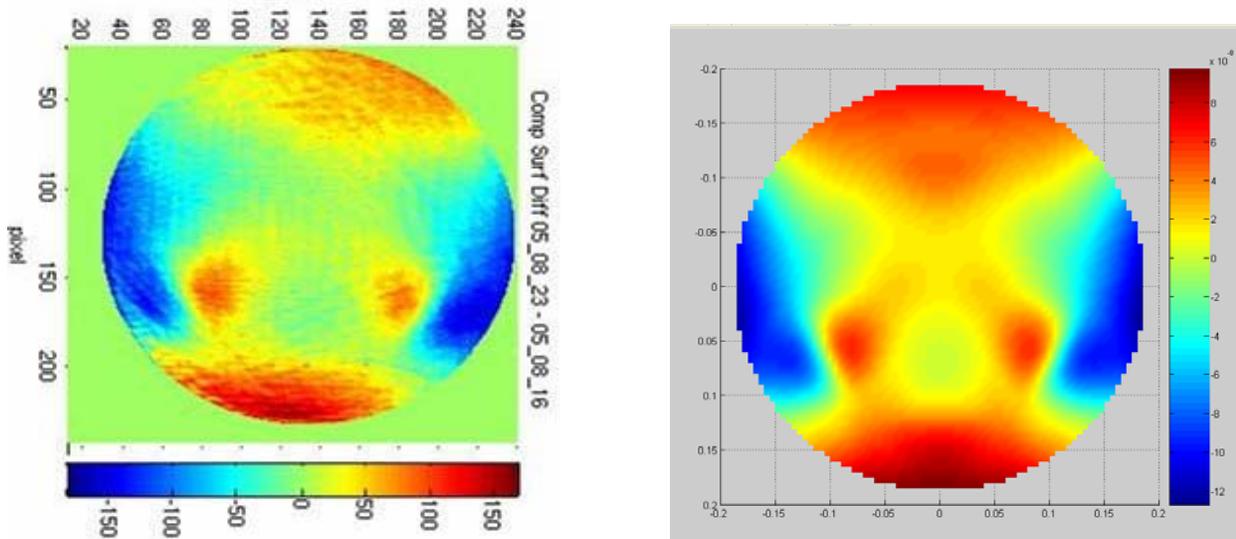


Figure 8 - M1 surface map measured during plunger test (left) and model results (right).

## 6. COMPRESSOR PHASE MAP ANALYSIS AND MODEL CORRELATION

During the investigation of the M1 mirror print-thru, a delta temperature soak case was also analyzed. During the TOM3 testing a temperature drop case was conducted and it was possible to perform a model correlation of the results. Figure 9 (left) shows the surface map of the TOM3 M1 mirror after a 8.4°K temperature drop. Figure 9 (right) shows the analytical results due to an increase of 1°K in temperature. A visual analysis demonstrates an excellent correlation between the measured values and the analytical results. The analytical results obtained with the finite element model showed an RMS value 15% higher than the test results. The P-V analytical results were less than 2% from the test results.

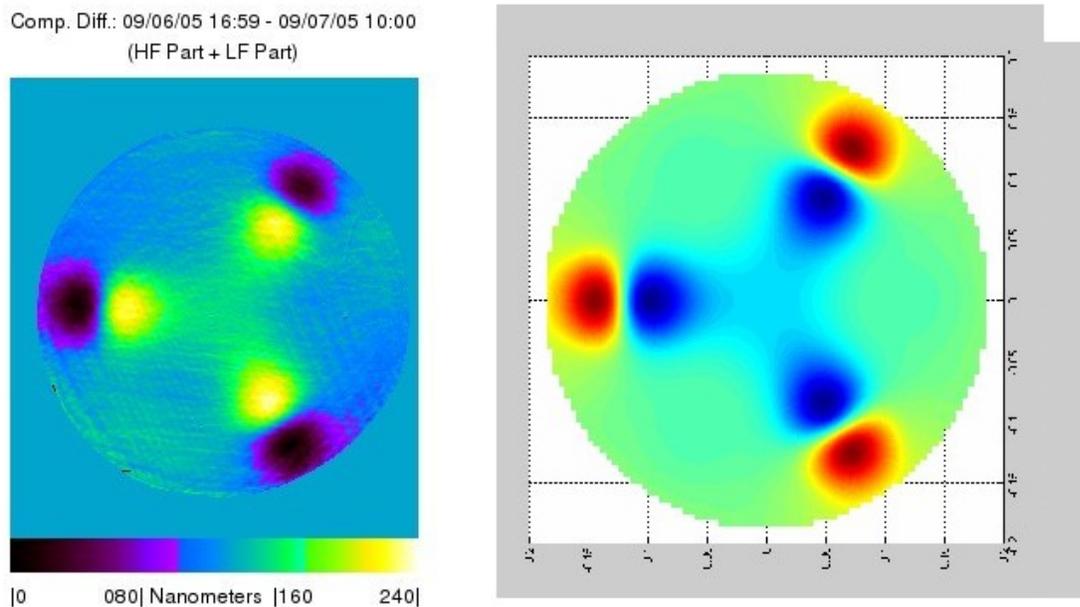


Figure 9 - Differences in phase map of the compressor compared to deformation map of the model with a 1°K delta temperature soak. Distortion of Mirror after a Uniform Temperature Drop 8.4 °K (measured, left). Uniform Temperature Increase of 1°K (calculated, right). (Note: Color scales do not match due to the different softwares used to plot the results)

## **7. CONCLUSIONS**

The TOM3 testbed served its purpose of detecting potential issues with flight hardware, not only during the testing itself, but also during the fabrication and integration of the hardware. Several lessons were learned in the process of manufacturing the M1 mirror. In particular, for the benefit of this paper, the one that stands out is the fact that the manufacturing process needs to be carefully studied. Also, thorough analysis needs to be conducted to help detect problems that may arise during fabrication. Every time the loading conditions during fabrication or testing deviate from the intended purpose of the article, it is very important to verify the new conditions through thorough analysis and either modify the process or account for the changes in a rational manner.

Through the use of this type of testbeds, several potential performance and process related issues are usually identified and solutions can be provided in time, without risking the flight hardware and a particular space mission. In general, the analytical results match very well the test results. In some instances where the analytical results did not match, the problems were understood well enough that, if necessary, a better correlation can be achieved by having more information on the test hardware. Having good results provides good confidence so that in the future we can avoid, in some instances, some of the costly testing.

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